Quantum simulation of quantum field theories

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We propose a digital-analog quantum simulation of fermion-fermion scattering in the context of quantum field theories (QFTs) with superconducting circuits. This quantum technology provides strong coupling between superconducting qubits with a microwave resonator, and a continuum of bosonic modes, which in turn allows us to implement a discrete set of fermionic modes interacting with the bosonic continuum. This effort may represent a significant advance towards full-fledged quantum simulation of QFTs in a controllable system.

QFT model

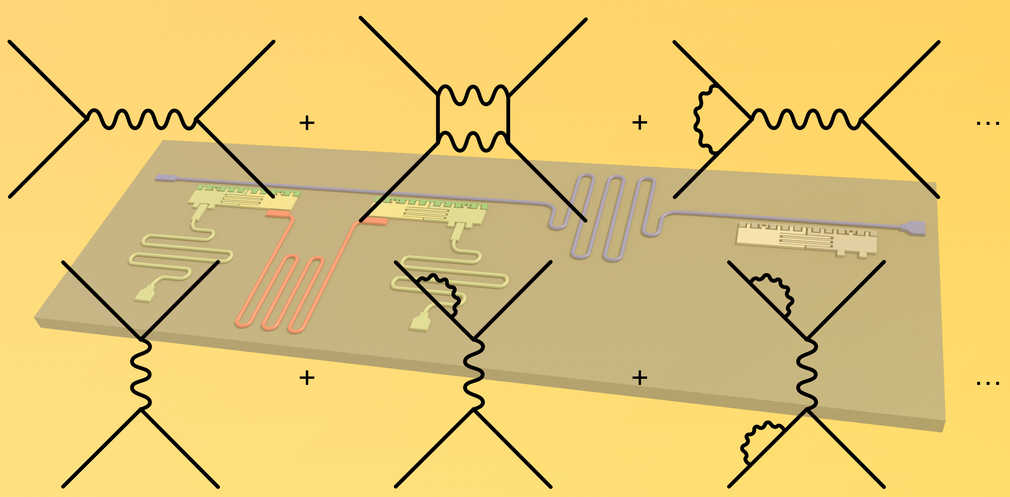
Interaction of scalar fermions and bosons in 1+1 dimensions

-Fermion-fermion scattering mediated by bosonic fields

-Fermionic self-energies

$$H = \int dp\ \omega_p (b_p^\dagger b_p + d_p^\dagger d_p) + \int dk\ \omega_k a_k^\dagger a_k + \int dx\ \psi^\dagger(x)\psi(x)A(x)$$

with $$A(x) = i \int dk\ \lambda_k \sqrt{\frac{\omega_k}{4\pi}} \left(a_k^\dagger e^{-ikx} - a_k e^{ikx}\right)$$



Nonperturbative regimes

Discrete fermionic field comoving modes interacting via a continuum of bosons

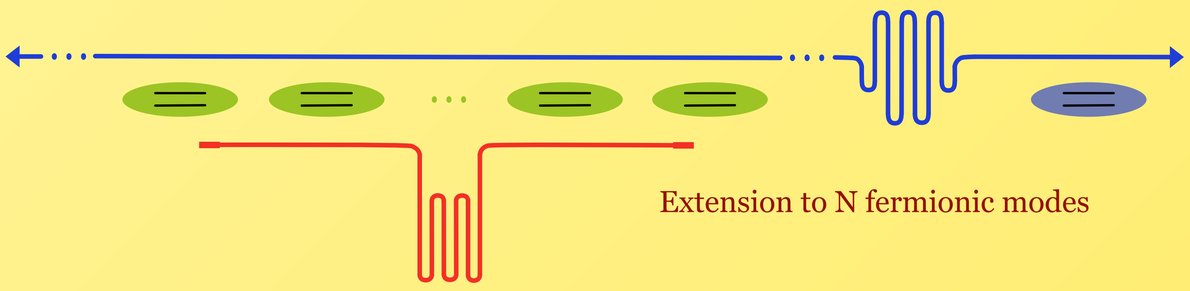
Jordan-Wigner transformation: three kinds of interactions

$$H_1 = i\sigma_j \int dxdk\ g_k \left(a_k^\dagger e^{-ikx} - a_k e^{ikx}\right)$$

$$H_2 = i(\sigma_j \otimes \sigma_\ell) \int dxdk\ g_k \left(a_k^\dagger e^{-ikx} - a_k e^{ikx}\right)$$

$$H_3 = i \int dxdk\ g_k \left(a_k^\dagger e^{-ikx} - a_k e^{ikx}\right)$$

Scalability



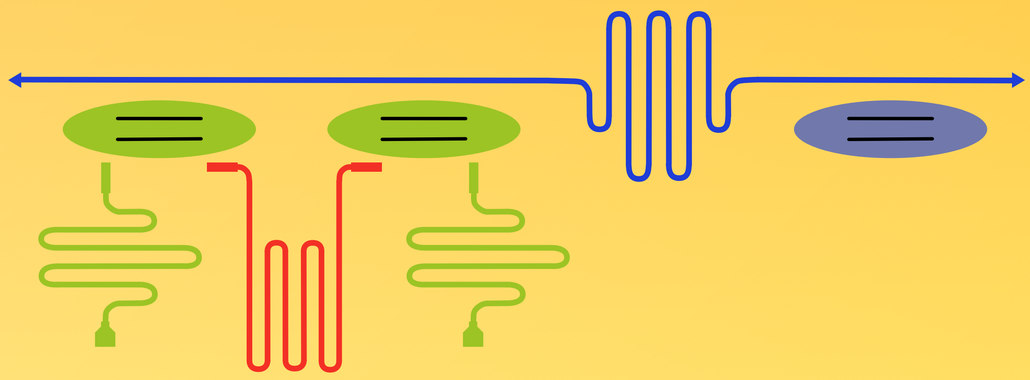
Superconducting circuit model

Circuit quantum electrodynamics architectures

-Microwave open transmission line

-Microwave resonator

-Tunable coupling qubits



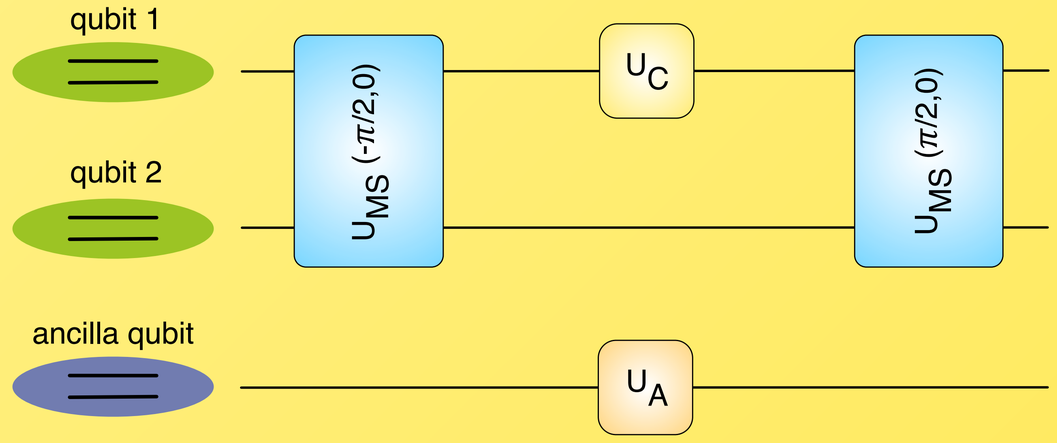
$$H_{\text{int}} = i \sum_{j=1}^{3} \sigma_j^y \int dk\ \beta(\Phi_{\text{ext}}^j, \bar{\Phi}_{\text{ext}}^j) g_k (a_k^\dagger e^{-ikx_j} - a_k e^{ikx_j}) + i \sum_{j=1}^{2} \alpha(\Phi_{\text{ext}}^j, \bar{\Phi}_{\text{ext}}^j) g_j \sigma_j^y (b^\dagger - b)$$

Operation sequence for the simulation

Generation of multiqubit gates coupled to the continuum

-Gates involving only the bosonic modes via an ancilla qubit

-Single-qubit gates coupled to the continuum



$$U_C = \exp\left[-\phi\sigma_1^y \int dk\ g_k \left(a_k^\dagger e^{-ikx} - a_k e^{ikx}\right)\right]$$

1 : L. García-Álvarez et al. Phys. Rev. Lett. 114, 070502 (2015)
2 : A. Mezzacapo et al. Phys. Rev. Lett. 113, 050501 (2014)
3 : J. M. Gambetta et al. Phys. Rev. Lett. 106, 030502 (2011)